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OXIDE-COATED BRUSH CATHODES IN
ELECTRON-BOMBARDMENT ION THRUSTORS**

by William R. Kerslake

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SUMMARY

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Initial experimental results with thick-oxide-coated wire brush cathodes have yielded thruster operating lifetimes in excess of 1000 hours. A 0.5-centimeter-diameter cathode operated in a 5-centimeter thruster for 1553 hours, and a 1-centimeter-diameter cathode operated for 3903 hours in a 7.5-centimeter-diameter thruster simulator. Another nominal 1-centimeter-diameter cathode operated 1250 hours in a 20-centimeter-diameter thruster. The radial wires in the brush design provided thermal and electrical conduction paths and reduced arc damage significantly. Each brush cathode at failure contained one-third or more of the original quantity of oxide. Greater cathode lifetimes should be attainable when present failure mechanisms are fully understood and corrective measures are applied.

INTRODUCTION

Author

Cathode types reported previously (refs. 1 and 2) for use in the mercury electron-bombardment thruster have not demonstrated a capability to attain the 5 000- to 10 000-hour lifetimes required for space missions. These cathodes failed because of excessive surface erosion due to ion-bombardment sputtering. Arcing in the discharge chamber and nonuniform temperature at the surface of the cathode also contributed to the deterioration of these units.

A wire brush cathode was designed to allow thicker oxide coatings to be utilized. The twisted wires on the axis of the spiral brush were used to carry the heating current, and the radial bristles were used to support mechanically the oxide and to provide direct thermal and electrical conduction from the heater wire. The design and operation of this type of cathode is described herein. Although the investigation to date has been limited to a small number of cathodes because of the lengthy nature of the tests, the preliminary results are considered to be of sufficient interest to electric propulsion technology to warrant early dissemination.

Ion thrusters employing 5- and 20-centimeter-diameter electron-bombardment ion sources were used in this study as was a 7.5-centimeter-diameter simulated

thruster. General descriptions of the ion thrusters and the simulator are given in references 3 and 4, respectively.

APPARATUS AND PROCEDURE

Cathodes

Design. - The thick-oxide-layer cathode of reference 2 with a 0.1-centimeter coating had lifetimes of several thousand hours in a simulated thruster. Based on the erosion rates given in reference 2, an oxide thickness of about 0.5 centimeter would be required for a 10 000-hour life. To permit the buildup of such a thick oxide layer with adequate mechanical support and to provide better thermal and electrical conduction through the oxide layer, a configuration was conceived in which thin wires are attached to a heavier center wire in the manner of a radial wire brush. The length of the brush is determined by the emission desired, with typical emission current densities of up to 1 ampere per square centimeter. The cathode sizes used in the various ion chambers as well as the material used to fabricate the brushes are given in table I.

In addition to being a thermal and electrical conductor, the brush material must possess adequate mechanical strength at cathode operating temperatures ($\sim 1200^\circ \text{K}$) and must be chemically compatible with the oxide coating. Previous tests have shown both tantalum and tungsten to be suitable, with tantalum normally used to avoid embrittlement problems. A 10-percent tungsten - tantalum alloy has been used for the heater wires to provide additional mechanical strength. The wire strength determines the minimum practical heater wire size, while the maximum size depends on heater current availability. The bristles must be closely packed to hold the oxide firmly and to provide the necessary thermal and electrical conduction paths. The bristle density at the surface of the 1-centimeter-diameter cathode used herein is about 400 bristles per square centimeter. Newly fabricated brushes were normally "combed" to provide a uniformly spaced array of bristles. In general, the ratio of twisted heater wire to bristle wire diameter should be between 5 and 10 to hold the bristles tightly. The minimum bristle wire diameter that could conveniently be fabricated from tantalum and tungsten was 0.004 centimeter.

Brush coating. - Figure 1 shows a 1-centimeter-diameter, 10-centimeter-long tantalum brush. Each bristle has a 0.008-centimeter diameter, and each of the four twisted wires has a 0.05-centimeter diameter. Half of the brush has been coated with Radio Mix No. 3 powder (57 percent barium carbonate (BaCO_3), 42 percent strontium carbonate (SrCO_3), and 1 percent calcium carbonate (CaCO_3)). The coating was put on the brush as a water slurry in repeated steps to fill voids that developed during drying periods. One percent of a wetting agent (aerosol-DT) was added to the water slurry to enable the water to better wet the carbonate powders.

Cathode activation. - The coated brush was mounted between heavy copper leads and placed in a thruster. The cathode was heated in steps to approximately 1400°K and maintained at that temperature for 5 minutes without electron emission. During this heating period the carbonates were converted to oxides

with the release of carbon dioxide. Cracks developed in the oxide coating between the bristles and were observed to have approximately 100° K higher temperatures than surrounding areas. No effort was made to refill these cracks.

Cathode temperatures were measured with a calibrated optical pyrometer. It was assumed that the cathode was a blackbody and that negligible losses occurred in transmission through a glass window.

The emission from the brush cathode after the low initial heating and final activation was achieved by exposure to the ion chamber discharge. Either a process of ion bombardment of the cathode surface (ref. 2) or an electrolysis of the oxide by drawing emission current (ref. 5) fully activated the cathode in 5 to 60 minutes.

Thrustors

Figure 2(a) shows the 5-centimeter-diameter discharge chamber used in the tests. The 0.5-centimeter-diameter brush cathode was mounted across two copper leads protruding through the radial flow distributor. Mercury was supplied by a steam-heated vaporizer. The 5-centimeter-diameter thrustor was operated in a 20-inch-diameter bell jar connected to a 5-foot-diameter by 15-foot-long vacuum tank. Further details of a similar thrustor of this size may be found in reference 3.

Figure 2(b) presents the 7.5-centimeter-diameter discharge chamber, which is denoted as the simulated ion thrustor in references 2 and 3. The 1.0-centimeter-diameter by 5-centimeter-long brush cathode was bent into a roughly circular shape and mounted from two parallel copper leads extending through the radial flow distributor. A single screen grid (50-percent blockage) was used because no high voltage was applied to extract a beam from the discharge chamber.

Figure 2(c) shows the discharge chamber of the 20-centimeter-diameter thrustor. The 1.0-centimeter-diameter by 10-centimeter-long brush cathode was mounted along the centerline of the discharge chamber. The parallel mounting rods were copper clad with alumina tubing. The changes in the flow distributor and cathode were the only changes made in this thrustor as compared to that reported in reference 4. The thrustor was operated in a 40-inch-diameter metal bell jar connected to a 5-foot-diameter by 15-foot-long vacuum tank by a 36-inch-diameter gate valve.

RESULTS

5-Centimeter-Diameter Thrustor

A single brush cathode was endurance tested for 1553 hours in the 5-centimeter-diameter thrustor. During this period the thrustor was shut down and restarted deliberately 54 times without removal from the vacuum chamber. The operating parameters are listed in table II. The thrustor output was maintained between 0.015 and 0.020 ampere of beam current by adjusting the cathode

heating power to give an emission of 0.2 to 0.4 ampere. The low propellant utilization efficiency was chosen for greater dependability of operation and to minimize the power-to-thrust ratio. The losses of propellant were considered acceptable in view of the anticipated use as a satellite station keeping or attitude control thruster. The strength and divergence of the magnetic field was experimentally selected to minimize discharge chamber loss per beam ion. A normal operating range for the discharge voltage was 20 to 50 volts. The final value of 35 volts was a compromise between a lower cathode sputtering rate at a lower voltage and a lower discharge chamber loss per beam ion at a somewhat higher voltage.

There were no high-voltage breakdowns except for several that occurred in the initial hour of operation with the new cathode. There were no low voltage arcs in the discharge chamber, even after the high voltage breakdown. During operation with the thick-oxide-layer cathodes investigated previously (ref. 2), destructive arcing between the oxide cathode and the anode (often precipitated by a high-voltage breakdown) was noted frequently.

The discharge in the chamber was lost for various reasons on the average of once every 50 hours. Typical reasons were (1) lowering the propellant flow due to a steam pressure drop at the propellant vaporizer, (2) liquid nitrogen flow stoppage to cold baffles, which resulted in a vacuum tank pressure rise that temporarily poisoned the cathode, and (3) fluctuations in the electric power supplies. In all cases, the discharge was restarted after returning to normal conditions of cathode heating power and discharge voltage by lowering and raising the magnetic field strength. It was also possible to start the discharge at a constant magnetic field strength by raising the discharge voltage to approximately 50 volts.

Figure 3 presents the cathode heating power as a function of operating time. Figure 3(a) is for the 0.5-centimeter brush cathode used in the 5-centimeter-diameter thruster. The cathode heating power required to maintain the beam current increased with operating time. The increase (with minor variations) was very slow until 800 hours. At this time an error developed in the beam current meter. The operator assumed the falsely low reading to be a fall-off in beam current and adjusted the cathode heating power upward to a 150-percent increase for 15 hours. When the meter error was discovered, the thruster operation was returned to normal with the cathode heating power at its previous value. From this point, however, there began an increase in heating power to a new level or plateau of about 22 watts. It is difficult to assess the effect of this 15-hour over-power period on the cathode lifetime, but a calculation of evaporation rates indicates one-seventh of the total oxides present on the cathode should have evaporated during this time. In contrast, at normal cathode operating temperature evaporation occurs so slowly that over 10^5 hours would be required to evaporate all of the oxides present.

After 1551 hours, there was a large pressure excursion in the vacuum facility to the 10^{-4} millimeter of mercury range. Although emission was reestablished after this excursion, one of the two cathode heater wires was broken, and the other failed after 2 hours of operation. There was little erosion of the heater wires, and the failure was in a portion well protected from direct ion

bombardment. The failure was thus felt to be from embrittlement, perhaps from the gases absorbed in the pressure excursion.

7.5-Centimeter-Diameter Simulated Thrustor

The first brush cathode fabricated (table I, line 2) was endurance tested for 3903 hours in the 7.5-centimeter-diameter simulated ion thrustor. The test was conducted without interruption of the bell jar vacuum or the electrical services to the simulated thrustor. The operating parameters are listed in table II. There were no arcs nor destructive damage to the cathode. The cathode emission briefly dropped off to near zero, or was out completely, on the average of once every 250 hours. The losses of emission were caused entirely by liquid nitrogen flow stoppage to the cold baffle surrounding the simulated thrustor. The bell jar had a much smaller pumping capacity than the 5-foot-diameter tank and was more sensitive to changes in the cold baffle temperature and the resulting release of condensed vapors that may chemically attack the cathode.

Figure 3(b) shows the cathode heating power as a function of operating time for the 1-centimeter-diameter brush in the 7.5-centimeter-diameter simulated ion thrustor. The heating required to maintain 4-ampere emission started at 60 watts, diminished to 45 watts at 900 hours, and then increased to 54 watts at 1000 hours. At 1900 hours the bell jar pressure increased because of liquid nitrogen baffle trouble, and subsequently, the cathode heating power increased to 100 watts at 2900 hours. The step changes of the cathode heating power always followed an inadvertent warming of the liquid nitrogen baffle. Gases released from the warmed baffle probably caused poisoning of the cathode. At 2900 hours a severe liquid nitrogen stoppage occurred, and a subsequent power increase to 110 watts was necessary.

After the first several hundred hours, the bristles of the brush seemed to protrude about 1 millimeter above the surface of the oxide coating. This protrusion would seem to indicate a rapid initial sintering or erosion of the oxide. At approximately 2500 to 3000 hours, the bristles no longer protruded as far. The bristles at some areas near the cathode middle seem to be flush with the surface, while other areas near the brush end had bristles protruding perhaps 0.5 millimeter. At 2000 hours the cathode surface was noted to have a dark deposit that probably had built up slowly. This dark deposit continued to build up and was very heavy at the end of the run. The diameter of the cathode at 3000 hours had shrunk no more than 20 percent (to ~0.8 cm). Between 3898 and 3903 hours the cathode heater resistance increased 25 percent, and at 3903 hours there was an abrupt break in the heater wires.

20-Centimeter-Diameter Thrustor

A 1-centimeter-diameter brush cathode has been endurance tested 1250 hours in a 20-centimeter-diameter thrustor. The thrustor was run continuously with one exception when the tank pressure increased to 10^{-3} torr before a minor leak was fixed. The emission of the cathode fell briefly to a low (5 percent of normal) value only twice during the 1250 hours of operation for reasons similar to

those previously mentioned for the 5-centimeter-diameter thruster. Some 273 high-voltage breakdowns occurred during the 1250-hour run. These breakdowns occurred with decreasing frequency (six during the last 200 hr). The thruster operating parameters are listed in table II. The choice of discharge voltage and current was again dictated by a compromise between low cathode sputtering (low discharge voltage) and efficient discharge chamber operation (moderate discharge voltage). A decreasing with time emission current of 8 to 4 amperes was necessary to give a propellant utilization efficiency of 0.9.

Figure 3(c) is a plot of cathode heating power as a function of operating time. The initial heating was about 75 watts, which continued until 300 hours. After this time the heating power showed a steady increase until 450 hours, at which time the rate of power increase lessened. The minor tank leak occurred at 750 hours, but no adverse effects on the cathode were evident in the data. When heating power had increased to 240 watts at 1100 hours, the discharge voltage was increased gradually to 48 volts to maintain a constant beam current rather than endangering a burnout of the cathode heater. The test was terminated at 1250 hours to allow inspection and measurements of the cathode.

The cathode used in the 20-centimeter-diameter thruster had been modified to reduce the diameter. The brush was pulled through a small hole which bent the bristles over in a chevron shape. In this condition the cathode held about 50 percent of the normal quantity of oxide. After the run, the cathode was estimated to contain one-third of the original oxide. When viewed normal to the cathode surface, all the visible oxide was covered by a dark deposit. White oxide was noticeable within the bristles however, when the cathode was viewed in a direction parallel to the wires. The increased heater power required toward the end of the test (despite the considerable amount of oxide remaining) indicates that bending the bristles over is not a desirable modification.

DISCUSSION

There were several general observations that seemed to apply to all the brush cathodes tested. First of all, there was no apparent loss of emissive (oxides) by material falling off the brush, which was the usual result of arc damage on the previously investigated thick-oxide-layer cathodes. During the tests, the bottom of the anode chamber was constantly observed for flecks of cathode material, but none were seen. Second, certain areas or regions of the brush cathode would glow hotter than normal for periods of seconds to several minutes. This behavior was probably the result of locally higher emission, which caused joule heating of this area. There was less tendency for the brush cathode to have pulsing hot areas than the thick-oxide-layer cathode of reference 2. When the brush did exhibit pulsing, this pulsing would randomly cycle off and on for several hours and then be quiet for periods of several hundred hours. These pulsing hot areas should be distinguished from the steady-state hot cracks and normal temperature gradients that continuously existed in the cathode. Finally, there was much less discharge chamber arcing when the brush cathode was used as compared to the thick-oxide-layer cathode of reference 2. In fact, the problem of cathode damage, due to low-voltage discharge chamber arcing, seemed to be eliminated when a brush cathode was used in a thruster with a diameter of 20 centimeters or less.

The ability of the brush cathode to resist arc damage may lie in its construction. Each bristle is a good thermal and electrical contact to the heavy central twisted wires. Thus, any voltage or thermal gradients that might be necessary to initiate an arc spot on the cathode surface were suppressed. In addition, the oxide erodes faster than the bristles, which then protrude above the surface and protect the surface from ion bombardment. The tantalum bristles are much more durable and resistant to arc damage than the powdery oxide coatings.

Due to the nonuniform temperature distribution in the cathode (e.g., hot cracks and local hot areas), it is possible that locations of high electron emission occurred. It is difficult to reach conclusions on emission densities from temperature measurements alone, as emission depends on temperature, surface work function, and depth of activation or conditioning. Conditioning can be a constantly changing property depending on local ion bombardment, heating, chemical attack, or surface condensation of sputtered material.

The previously noted calculation on evaporation rate indicates a negligible amount of evaporation (corresponding to a 10^5 -hr lifetime) at normal operating temperature. The rates were higher at the hot cracks (perhaps by a factor of 100). If, however, the oxide were evaporated from the vicinity of the cracks, the emission could still emanate from neighboring zones of unused oxide for long periods of time. Even though cathode sputtering erosion cannot be accurately calculated, estimates indicate a surplus of oxide material for a 10^4 -hour lifetime with a 1-centimeter-diameter brush cathode. Visual inspection indicates an abundance of emissive material on all the brush cathodes, even when they began an increasing heater power. A lack of emissive material does not seem to be the problem.

One possibility to account for the gradual increase in heater power is that the oxide remaining on the cathode becomes less available for emission of electrons. A possible mechanism is that material sputtered off the distributor and screen was recondensing on the cathode and increasing the local surface work function. A calculation indicates that 3×10^{-3} ampere per square centimeter of mercury ions striking the distributor would sputter enough mass to coat the cathode with a monolayer in 10 hours. These monolayers may build up faster than they are cleaned off by evaporation and ion bombardment if surface absorption energy for thin layers is greater than the normal energy required for evaporation. Colder cathode areas would be expected to build up a thicker condensed layer; hence, the oxides under this layer would become less available.

CONCLUDING REMARKS

A new type oxide-coated cathode, in the form of a tantalum wire brush, has undergone preliminary testing in electron-bombardment ion thrusters. Sufficient quantities of oxide have been incorporated into the construction of the brush cathode that the losses due to ion-bombardment sputtering appear to be small, and those due to normal evaporation are almost certain to be negligible. Low-voltage arc damage also seems to have been eliminated as a cathode destruction

mechanism. At this time, the probable failure modes and ultimate lifetimes have not been determined. Nevertheless, the first tests with brush cathodes have achieved encouragingly long operating lifetimes in the range of 1250 to 3900 hours.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 27, 1965.

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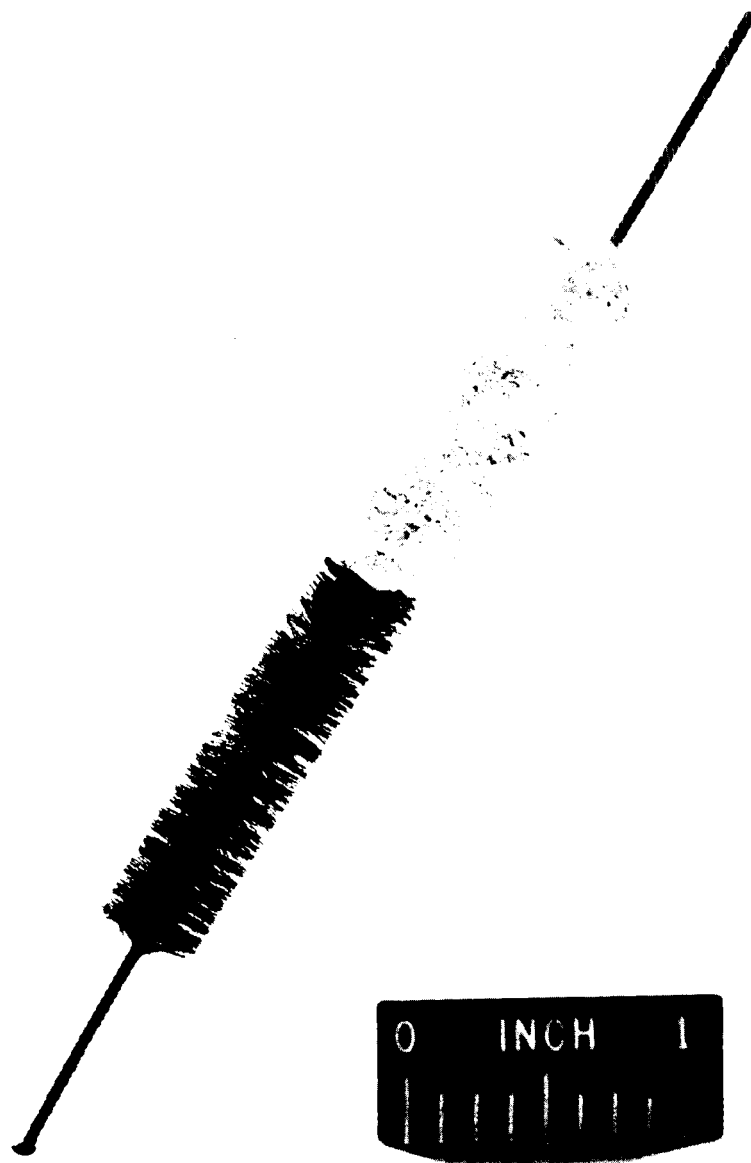
TABLE I. - SPECIFICATIONS OF BRUSH CATHODES

Thruster diameter, cm	Brush		Twisted (center) wires			Bristle wires		
	Diameter, cm	Length, cm	Material	Diameter, cm	Number of strands	Material	Diameter, cm	Number of bristles/sq cm
5	0.5	1.2	Tantalum	0.025	2	Tungsten	0.005	450
7.5	1.0	5.0	Tantalum	.050	4	Tantalum	.008	400
20	1.0	10.0	Tantalum	.050	4	Tantalum	.008	400

TABLE II. - AVERAGE THRUSTOR OR DISCHARGE OPERATING
PARAMETERS FOR BRUSH CATHODE TESTS

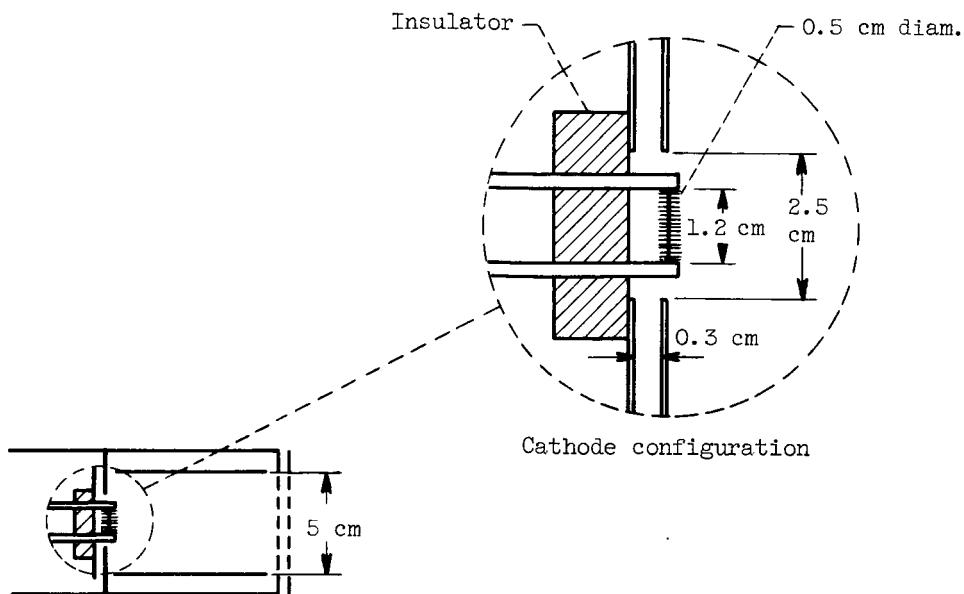
	Thruster size (anode diam.), cm		
	5	7.5	20
Cathode surface area, sq cm	1.9	15.7	31.4
Discharge voltage, V	35	30	33
Cathode emission, A	0.2	4.0	5.0
Magnetic field, G			
Screen	27	25	15
Distributor	60	34	25
^a Cathode heating power, W	15	60	100
Cathode temperature, °K	1300	1250	---
Ion beam current, A	0.017	None	0.30
Mercury flow rate, A	0.034	0.16	0.34
Anode voltage, V	4000	30	3900
Accelerator voltage, V	-1000	None	-1100
Length of test, hr	1553	3903	1250

^aSee fig. 3 for cathode heating power details.

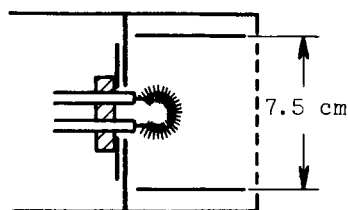


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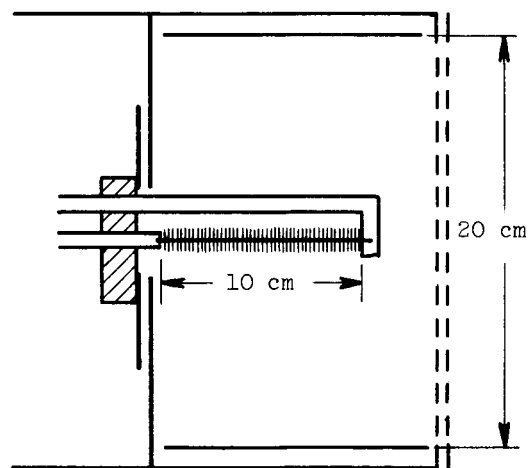
Figure 1. - Tantalum brush cathode half-coated with Radio Mix
No. 3 powder.



(a) 5-Centimeter-diameter thruster.

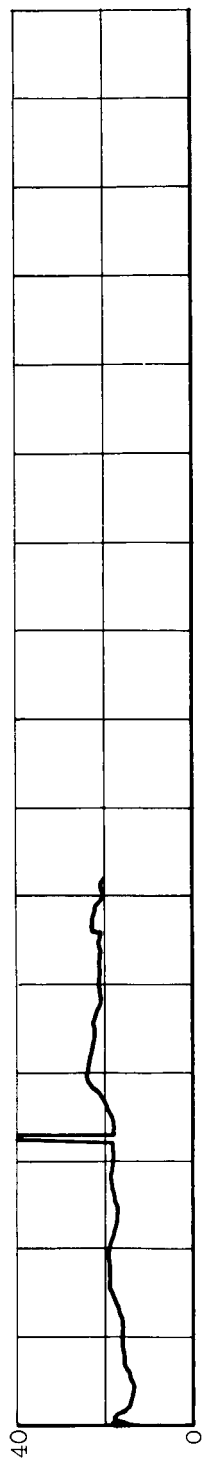


(b) 7.5-Centimeter-diameter simulated thruster.

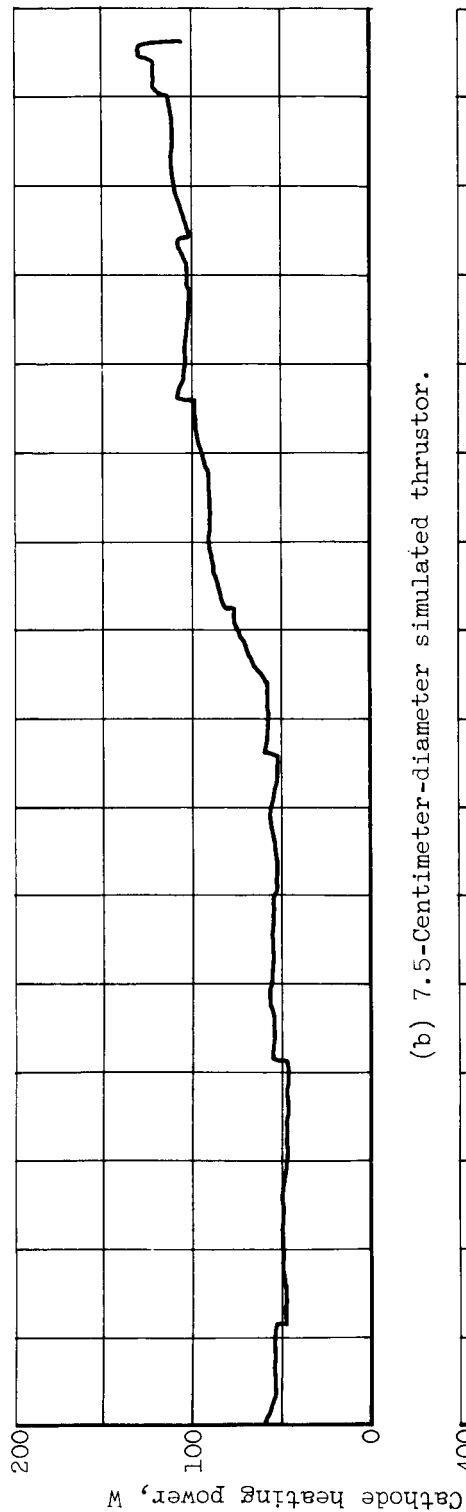


(c) 20-Centimeter-diameter thruster.

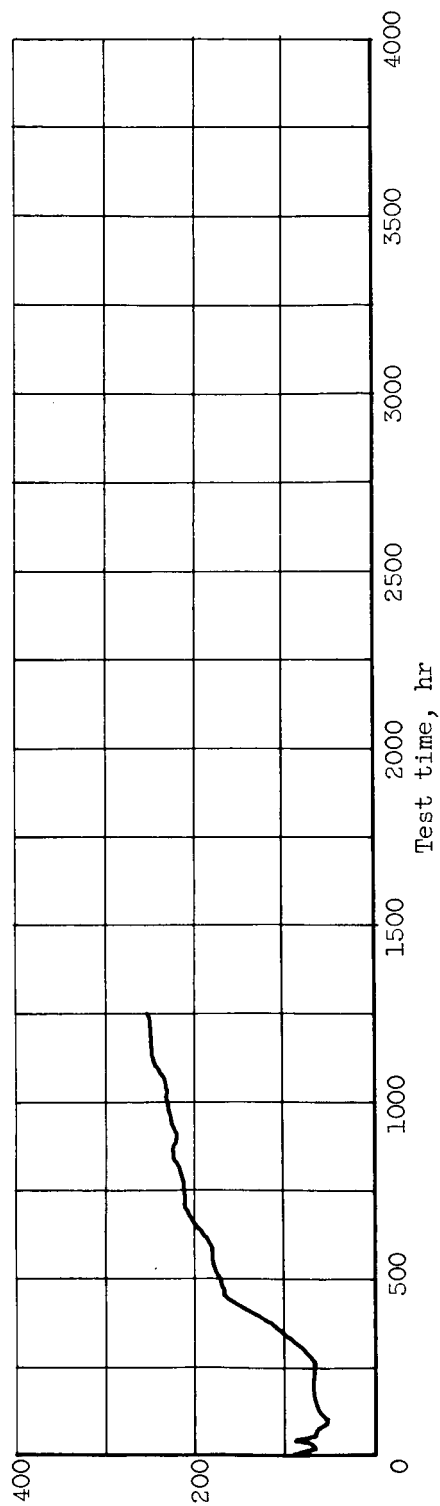
Figure 2. - Diagrams of discharge chambers. (See table I for cathode dimensions.)



(a) 5-Centimeter-diameter thruster.



(b) 7.5-Centimeter-diameter simulated thruster.



(c) 20-Centimeter-diameter thruster.

Figure 3. - Heating power as function of test time for three different brush cathodes.
(See table I for brush sizes.)